CONTROL LAW IMPLEMENTATION FOR MULTI-ISO: A TRAINING MACHINE FOR LOWER LIMBS

S. Moughamir, N. Manamanni, J. Zaytoon and L. Afilal
Université de Reims Champagne Ardenne
Laboratoire d'Automatique et de Micro-électronique
LAM, Faculté des Sciences - Moulin de la housse BP 1039 51687 Reims Cedex 2

Abstract- **This paper presents the control system of a machine for training and rehabilitation of lower limbs. This system is based on the execution of a sequence of switching (position, speed and force) control laws corresponding to the required training configuration. Some illustrative training results are also discussed.**

Keywords- **Rehabilitation machine, training machine, fuzzy logic control, switching control laws, weight machine.**

I. INTRODUCTION

Multi-Iso (Fig. 1) is a computer-controlled machine for training and rehabilitation of the lower limbs. This machine, which is destined for medicine and sports, is the result of a joint project involving the *Laboratoire d'Automatique et de Microélectronique* (Reims-France) and the company *Myosoft* (Bellegarde-France). Multi-Iso is based on original concepts that provide significant improvements over existing machines, including precise rehabilitation adapted to user needs, and dedicated training possibilities to improve physical performance and autonomy.

Fig. 1. Multi-Iso.

The architecture of Multi-Iso (Fig. 2) comprises a software and control part, a mechanical part, and an electronic part. The functioning principle consists in applying a torque delivered by a brushless motor to one (or both) lower limb(s). This motoring action allows the user to attain a nominal force of 200 deca Newtons (daN) at the ends of the limbs and a speed of 400°/sec under maximum load. Six other motors, not shown in Fig. 2, are also used to position the seat, either manually or automatically to a memorized position, so as to suit the needs and the morphology of the current user [1].

Multi-Iso can carry out different training configurations whose importance in medicine and sports are discussed in [1]. Seven training modes (*Isokinetic*, *Steering*, *Isometric*, *Isotonic*, *Physiokinetic*, *Stretching*, and *Assisted*) are implemented, and some of them are original and were developed specifically for Multi-Iso [2]. The specific training sessions, defined by a physiotherapist with the help of a domain-specific man-machine interface, are translated into a corresponding switching sequence of force, position or speed control laws that perform the required movement patterns. Training results are stored in a database to be subsequently processed. The control system comprises a PC-based supervisory module that handles the organization and the coordination of the activities involved in the training sessions, and a micro-controller-based module implementing the switching control laws.

This paper presents the control system of Multi-Iso; the synthesis of the switching control laws will be particularly emphasised. Some training results are given to illustrate the efficiency of the control system, despite the simplicity of the implemented control laws.

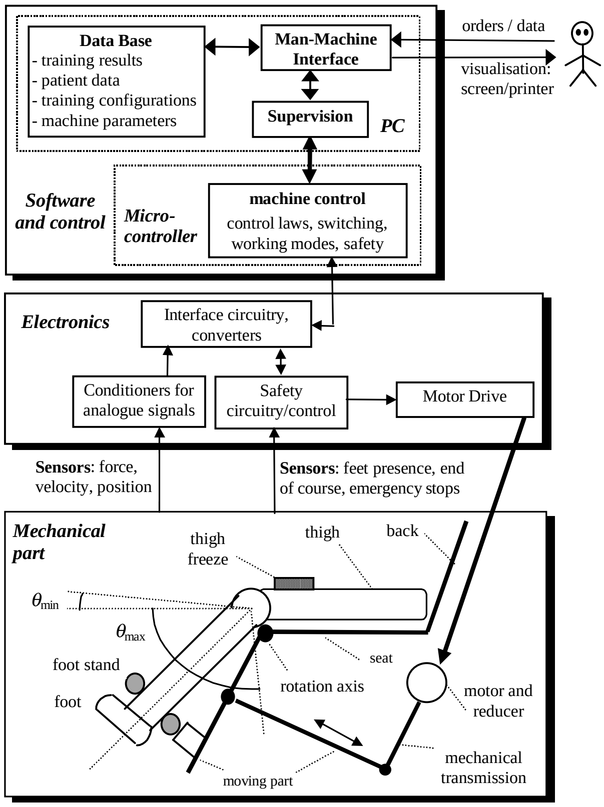

Fig. 2. Architecture of Multi-Iso.

II. CONTROL SYSTEM OF MULTI-ISO

The control system of Multi-Iso (Fig. 3) belongs to the class of switching systems, which is a sub-class of hybrid dynamical systems. The established medical specifications

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[1,2] have shown that three control laws (position, velocity, and force) are required to carry out the different movements. The switching sequence between these control laws depends on the nature of the exercise to be realized, the angular position of knees, and the patient's force.

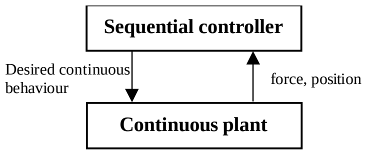

Fig. 3. Hybrid structure of the control system of Multi-Iso.

The sequential controller is based on hierarchical specifications given in terms of Statecharts [3] formalism. The established specifications, which are presented in an accompanying paper [4], are generic and hence they can be used for any training machine for the lower limbs.

The switching control scheme depicted in Fig. 4 shows the three control laws: velocity (L_ω), force (L_f) and position (L_θ). The activation of these control laws depends on the variable i (i $\in$ {1,2,3}) delivered by the discrete controller. Given the nonlinear model [1] of Multi-Iso and the uncertainty related to its parameters, a fuzzy velocity control law has been used as an inner control loop for the switching system. The inner control loop guarantees the asymptotic stability of the system. Hence, when a switching sequence of control laws occurs, the applied control law (L_f or L_θ) generates a velocity reference, ω_{ref}, and the system remains stable thanks to the inner control loop.

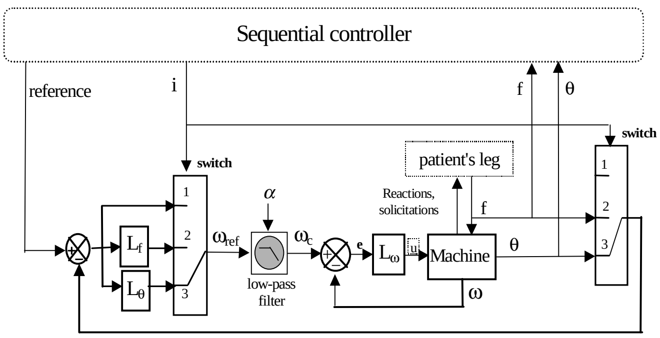

Fig. 4. Switching control scheme.

In order to guarantee the continuity of the control variable, ω_c, when switching between the control laws, a practical solution based on the use of a numerical filter was developed to guarantee a smooth behaviour of the system (a law switching frequency), and, by consequence, to ensure the user comfort. The value of the parameter α, which conditions the filter bandwidth is fixed experimentally for each user and, generally speaking, this value is small for training sessions and large in the case of rehabilitation exercises.

A. Velocity control law

Essentially used during *Isokinetic* and *Steering* training or rehabilitation modes, the main goal of the velocity control law is to guarantee a constant velocity without static error in order to avoid the drift of the moving part of the machine when the reference is zero. To meet these requirements, it is necessary to set up an easy to implement controller that takes model non-linearities into account. Furthermore, the control should be robust towards the model variations induced essentially by the man-machine mechanical interactions. Consequently, a fuzzy-logic controller [1] was used with the classical four-module structure depicted in Fig. 5 [5].

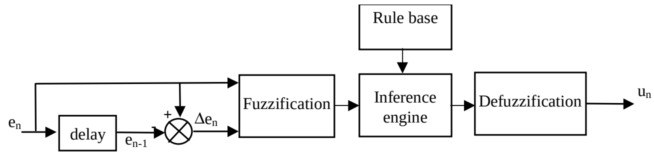

Fig. 5. Fuzzy controller for velocity control L_ω.

Five fuzzy sets were used for each of the variables *e*, Δe and *u*. For ease of implementation, the membership functions for the error signal, *e*, were chosen with triangular shapes and saturation, whereas those related to error variation, Δe , and output, *u*, were chosen with simple triangular shapes. The inference rules were established on the basis of the practical knowledge of the behaviour of the machine in view of obtaining an error and an error variation of zero. The fuzzy controller output, corresponding to control variable *u*, is obtained by using the *MAX-MIN* composition method as well as the centre-of-gravity method to guarantee a uniform influence of each rule during the deffuzification [6].

Unlike the classical techniques used in robotics, which introduce several feedbacks (non-linear compensation of the gravity plus the velocity feedback), the implementation of the fuzzy controller is rather simple because it only uses one feedback reaction. The implemented controller achieves a zero steady-state velocity error and compensates the effects of the potential energy and the force applied by the user. The controller is tuned to obtain a short rise time relatively to the reaction time of high-level sportsmen, which is equal to 125 *ms* ± 20% [7]. The machine can, therefore, be used in extreme training conditions. Moreover, the controller was shown to be robust towards parametric disturbance due, for example, to the adaptation of the patient's seat configuration.

B. Position control law

The position control law is used in the *Isometric* training mode where the patient needs to apply a maximal force around a fixed number of positions determined by the physiotherapist. On the other hand, this law is applied near the extreme positions of training movements to realize a smooth deceleration towards the final position. Position control is implemented by feeding the output of a proportional controller to the velocity control loop. This simple and easy-to-implement solution guarantees a zero steady-state position error without overshoots.

C. Force control law

This control law, which is used during the *Isotonic*, *Physiokinetic*, *Stretching*, *Assisted*, and free movements, is original because its objective is not to maintain or to follow a

desired reference (as is the case for the position and velocit control laws), but to simulate a variable mechanical load. The load imposed by the simulated weight machine can be chosen to meet the required medical specifications, and hence to 'provide' a machine adapted to the user needs. Thus, the aim of the force control law is to make Multi-Iso behave like a classical weight (training) machine, while avoiding the drawbacks of these machines, such as the losses caused by the transmission system and the impossibility to train the limb both in extension (upward movement) and flexion (downward movement) at the same time.

The dynamical model of an ideal weight machine (Fig. 6) can be expressed as follows:

$$J_0.\dot{\omega}_{ref} = F_{ref}.l - F.l - f_0.\omega_{ref}$$
$$F_{ref} = M.g$$

where l is the length between the point of effort application and the rotational axis; f_0 and J_0 represent, respectively, the viscous friction and the inertia of the moving part. A particular tuning of these parameters gives a specific reference model, and, consequently, a specific weight machine, tailored for a given user needs. The force F_{ref}, due to the load M, represents the desired force to be applied b the patient to balance the system.

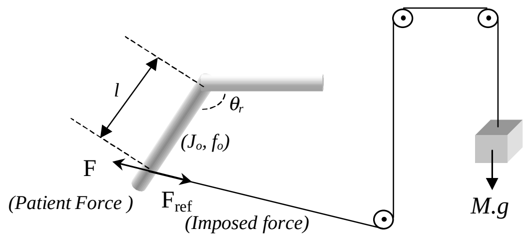

Fig. 6. Model of a weight machine.

Figure 7 depicts the established force control law, which uses the previous model as a reference model. As in the case of the position control law, the force control law re-utilizes the velocity control loop; the reference model gives the required velocity profile ω_{ref} of the weight machine whe submitted to an external force. The main objective here is to let the mobile part of Multi-Iso achieve the same velocity behaviour. Consequently, the velocity computed from the reference model is used as desired input for the fuzzy velocity control loop.

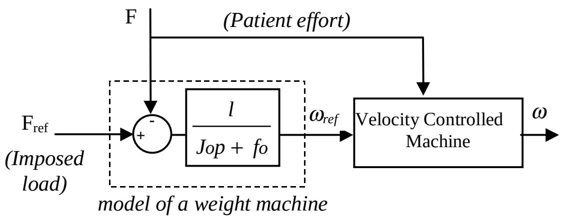

Fig. 7. Force control law.

Many experimental tests were carried out to validate the established force control law. Figure 8 depicts an experimental case with an imposed force, F_{ref}, of *20 daN*. This result shows that the velocity of the machine, ω, closely follows the required velocity profile, ω_{ref}. This case corresponds to an oscillatory force pattern, where the user applies a force greater than, and then less than, the imposed force.

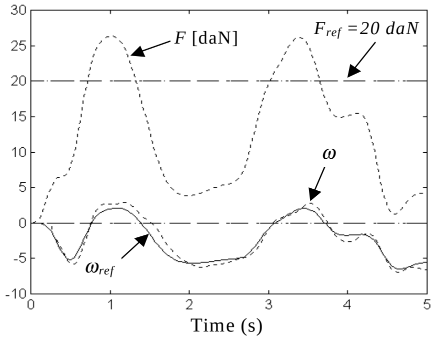

Fig. 8. Experimental results.

III. RESULTS

The following results illustrate the contribution of Multi-Iso in the sports domain as well as the performance of its control system and its adaptation capacity for each user.

Many training sessions was carried out by five sportswomen who were students in the Sports Department of the University of Reims. The value of α was fixed to adapt Multi-Iso's dynamics to every user. These training sessions followed a protocol devised by a physiotherapist to improve the muscular force of the *quadriceps*, through the execution of *Isokinetic* movement at a speed of 60°/s. The physical exercises proposed here were carried out during a period of three weeks with four training sessions per week. They involved *Concentri* -type movement for a group of three sportswomen, and simultaneous *Concentric* and *Eccentric* movements for the other group of two.

Every session started with a warming-up phase of two series comprising several repetitions. After a relaxation period, a second phase, used for evaluation, involved three series carried out with the sportswomen applying their maximum force. This evaluation phase provides the curve of average effort, which gives the work and power developed at each session, and illustrates the progress of the force-peak throughout the sessions. Next, the actual *Isokinetic* training phase starts with two series of three repetitions each, then four series of six repetitions, and, finally, one series of ten repetitions.

The results of the most consistent sportswoman of each group are presented in Figs. 9 and 10. Figure 9 shows, for each week, the average values of the evaluation curves related to the first sportswoman. The evolution of the effort (Fig. 9a) shows an improvement of the force peak, going from *80 daN* in the first week to more than *120 daN* in the third. This training period resulted in an average progression of 40% for the developed maximum force as well as a widening of the application range of this force (Figs. 9a and 9b). These results are confirmed by the ‘fatigue’ curves (Fig. 10c) characterizing the physical endurance throughout a series. An increase in force is noted throughout the three

weeks, as well as a flattening of these curves, reflecting a reduced muscular fatigue for the attained force level.

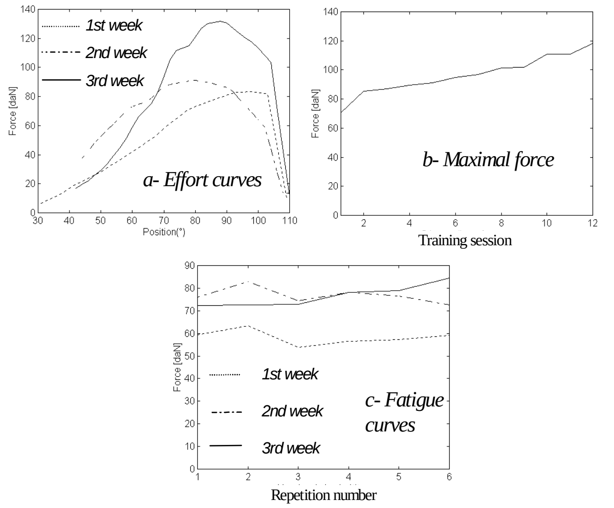

Fig. 9. Results of the Concentric training protocol.

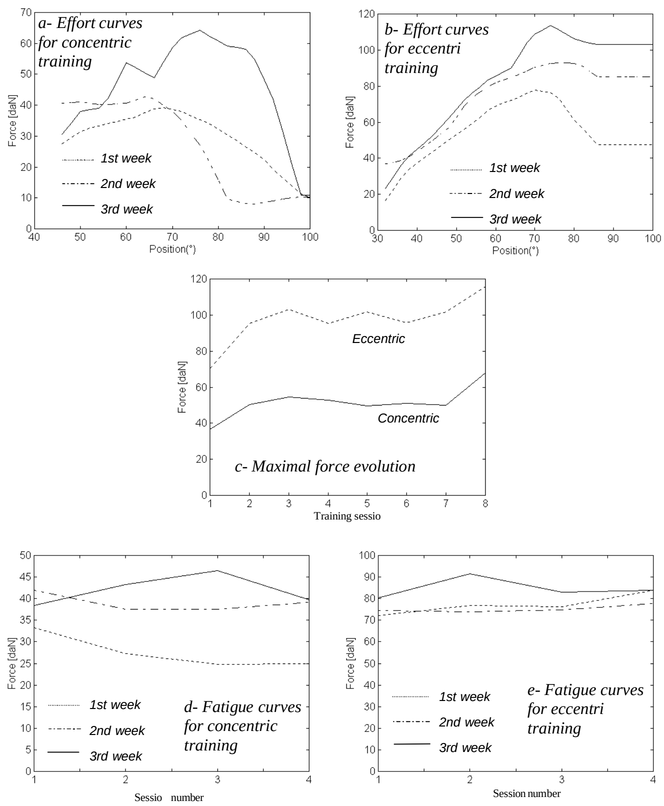

Fig. 10. Results of the Concentric-Eccentric training protocol.

The results for the second sportswoman reveal a significant increase in the effort curves (of the quadriceps) for both *Concentric* (Fig. 10a) and *Eccentric* (Fig. 10b) training. It can also be noted that the progress of the maximal force (Fig. 10c) is more significant in the *Eccentric* mode (40%) compared to the *Concentric* mode (25%). This observation confirms the findings of Albert [8]. Finally, the 'fatigue' curves, here characterizing the physical endurance throughout a series, are flattened throughout the three-weeks training period in the *Concentric* case (Fig. 10d). This implies an increase of the subject endurance for this training mode. On the other hand, the smoothness of the curves of Fig. 10e implies that the subject's performance was already high in the *Eccentric* mode.

V. CONCLUSION

This paper has presented the switching control system of Multi-Iso: a machine for training and rehabilitation of the lower limbs. This control system confers significant improvements to Multi-Iso over existing machines, including precise rehabilitation and dedicated training possibilities.

Current research work is related to the development of a fuzzy estimator for on-line adaptation of the filter bandwidth (parameter α of Fig. 4) to tailor the machine to the current user needs and physical state: comfort, sensations, fatigue and cardiac condition, etc. In parallel, another machine, based on identical concepts, is currently under development for training and rehabilitation of the upper limbs. The constraints imposed on the control system of this machine are far more severe than those related to Multi-Iso, due to the complexity of arm movements and the consequent safety constraints to be satisfied.

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